Backscattering by Non-spherical Natural Particles: Instrument Development, IOP's, and Implications for Radiative Transfer

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LONG-TERM GOALS

(i) Quantify and understand the inherent optical properties (IOP's) of natural particles from a standpoint of measuring size-distribution;

(ii) Understand how the properties of particles (composition, shape, and internal structure) affect their IOP.

*(iii)*Incorporate these properties into radiative transfer models for prediction of downwelling and upwelling radiances.

SCIENTIFIC OBJECTIVES

- We are developing a version of the LISST-100 forward scatter instrument that will deliver the same high-quality data in backscatter,

- The data will guide analytical light-scattering model development with such observations, and

- The results will be applied to predicting light propagation in the sea by providing as input, the new estimates of IOP's.

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This work is relevant to ONR's Sensor and Systems and Modeling thrust areas. It will contribute to understanding of how the shape of oceanic particles affect backscattering and provide an instrument that specifically addresses backscattering near 180 degree - a crucial parameter to understand, predict, and invert LIDAR signal. The LIDAR signal is proportional to the VSF near 180 degrees.

APPROACH

We describe the distinct tasks in the proposed program, identified with person responsible:

- *Development of a backscatter version of the LISST instrument* (Agrawal).

- *Characterization of scattering from terrigenous and biological size-sorted non-spherical particles* (Agrawal, Boss).

- *Field observations of backscattering of marine particless*(Agrawal).

- *Modeling of light scattering* (Boss).

- *Modeling of Radiative Transfer* (Mobley).

WORK COMPLETED

a. Development of a backscatter version of the LISST instrument (Agrawal). This device has been fully developed. It employs a powerful doubled YAG laser and a CMOS array combination as source and detector. The instrument is autonomous, powered by a separate battery pack. It incorporates measurement of beam attenuation as well.

The field instrument has been completed. A CMOS 2-D array is employed to capture not just the angular backscatter, *i.e.* $\beta(\theta)$, but also structure in φ which has been reported earlier by us. We have built-in the capability to observe the Mueller matrix in backscatter, which will only be pursued after the primary objectives are met. The instrument has been deployed off the Martha's Vineyard Coastal Observatory (MVCO) in a coordinated experiment with other investigators. The instrument was recovered on 24 September. Data view will begin later next week (10/1) after receiving the instrument in Bellevue, Washington.

b. Characterization of scattering from terrigenous and biological size-sorted non-spherical particles (Agrawal, Boss). In a significant advance, the small-angle forward scattering phase functions of random shaped natural particles have been characterized, and submitted to JGR-Oceans (Agrawal et al., 2007; *in revison.*).. Laboratory observations of the same particles in backscatter, sorted by settling size are in progress. Also, under study is the variability of scattering in the back-direction of a few different phytoplankton (with different morphologies, internal structure, and community structure (e.g. chains).

c. Field observations (Agrawal)*:* The instrument was deployed for a bottom boundary layer observation in the end of September 2007).

d. Modeling of light scattering (Boss)*:* Theoretical modeling of light scattering by randomly oriented non-spherical particles have been carried out and a review paper has been published (Clavano et al., 2007). We have published a manuscript, entitled 'Inherent optical properties of non-spherical marine-like particles—from theory to observation' in "Oceanography and Marine Biology: an Annual Review". Besides reviewing the state-of-the-art, we have derived many new results. In particular, we have extended a method to model the IOPs of individual, randomly oriented, spheroids using a polydispersions of spheres (Paramonov, 1994) to model marine-like particles. This allows us to model populations of marine-like particles throughout their relevant size range.

We have assembled all the T-matrix solutions performed at the Cornell Theory Center supercomputing facility and posted them on our web site for all (http://misclab.umeoce.maine.edu/research/research10_data.php). We also posted there the codes used to generate apply the Paramonov (1994) method.

Theoretical results focusing on backscattering were presented at the Ocean Sciences conference in Honolulu, HI (Clavano et al., 2006). In that presentation we compared measured near backward VSF and its polarization charachteristics obtained with the new backward LISST device with theoretical T-matrix results.

We have analyzed how phytoplankton shapes affect inversion of VSF into size distribution (Karp-Boss et al., in press). We found that a narrow size distribution of nonspherical particles act similarly to wide polydispersion of spherical particles, and that, the mode size is of the population of nonspherical phytoplankton is larger than that for spheres of the same volume. Both results are consistent with the theoretical analysis of Clavano et al., 2007.

e. Modeling of Radiative Transfer (Mobley): Work is in progress, pending definitive data from experimental and field observations for use in the models.

RESULTS

1. *Development of a backscatter version of the LISST instrument* (Agrawal): In figure 1, we show the layout and actual photo of the LISST-Back instrument. The instrument optics employ a 250mW doubled YAG laser. Backscatter optics employ a CMOS array for detection of azimuthally detailed backscattering. Data is stored on 2GB memory card. When the low-battery use electronics are implemented, the system will be able to record nearly two thousand images which can be converted to backscatter VSF, and the measured beam attenuation.

2. *Characterization of scattering from terrigenous and biological size-sorted non-spherical particles* (Agrawal, Boss): We first report on findings of small-angle forward scattering volume scattering functions. This work, carried out using sieved size fractions (16-500 microns) and particles sorted in a new-concept density-stratified settling column (2-16 microns) has confirmed earlier work by Konert and Vandenberghe (1997). We find that the phase functions of random shaped grains appear equivalent to a distribution of spheres of slightly mean size. Also it was found that fine particles (2-6 microns) appear to be equivalent to spheres of slightly larger size, but in addition, to a superfine mode. This has helped to explain the rising edge at the fine end of size spectra measured by LISST instruments. The volume scattering functions are reported first in a paper in revision, from the sediment transport viewpoint (Agrawal et al., 2007). An optical manuscript may be prepared to highlight changes from

Mie theory with an optics interest. In figure 2, we show the LISST-100 view of light scattering per unit concentration from random shaped particles (left) and from spheres (right). As described by us (Agrawal et al. 2007), much of the structure of Mie scattering is lost with random shapes. However, scattering shapes are distinct, permitting inversion of multi-angle data to construct a size distribution that does not require spherical shape assumptions.

The consequence of this shape effect is seen with inversion of multi-angle scattering to construct size distributions. Using data from the Santa Cruz experiment (Thorne et al. 2007), we show a segment of a storm event, Figure 3.

Switching now to backscatter properties, we illustrate azimuthal variation in light scattering from spheres, Figure 4. Figure 4 (left)shows light intensity on a CMOS array placed at the back focal plane of the receiving lens of LISST-Back. The direct on-axis backscatter corresponds to the tail end of the long arrow in the figure. The long arrow itself represents scattering angle. An azimuthal variation is highlighted by a short arrow. In other words, spherical particles exhibit oscillations not only on scattering angle (θ), but also an azimuthal variation (ϕ). Figure 4(right) shows laboratory data and theory showing excellent agreement for spheres.

In contrast to spheres, limited work has been completed with random shaped grains. Further progress is expected shortly. Early indications are that the structure seen in Figure 4 is diminished, or vanishes for random grains.

As part of our study of effects of non-sphericity on optical properties we have analyzed how phytoplankton shapes affect inversion of VSF into size distribution (Karp-Boss et al., in press). We found that a narrow size distribution of nonspherical particles act similarly to wide polydispersion of spherical particles, and that, the mode size is of the population of nonspherical phytoplankton is larger than that for spheres of the same volume. Both results are consistent with the theoretical analysis of Clavano et al., 2007.

3. *Field observations of backscattering of marine particless*(Agrawal). As of the time of this writing, the data (hopefully) collected by the LISST-Back instrument in the September 25, 2007 deployment is to be offloaded and processed. The instrument is in transit from WHOI to Sequoia.

4. *Modeling of light scattering* (Boss). We do not have the space here to detail all of the results we found with respect to the optical properties of non-spherical particles. The paper can be downloaded from (http://misclab.umeoce.maine.edu/publications/review_articles.php). A few notable ones are:

> **a**. Non-spherical particles, in general, have peaks in the volume (or mass) specific scattering, attenuation and backscattering which occur for larger sizes than equal-volume spheres. This implies that non-sphericity changes the relative contribution of different size particles to IOPs (Fig, 3). For absorption, randomly oriented non-spherical particles are found to absorb more per mass than equal volume sphere, a consequence of them being less packaged, e.g. more of the internal material is available to interact with light.

b. In accordance with the theoretical predictions randomly oriented particles were found to have volume scattering function which have larger forward peaks in comparison with spheres of the same size (Fig. 4). This is consistent with the lab experiment we have derived with random shapes and has been added to the paper through the last parts of its production.

c. Polydispersions of particles with constant or varying shape as a function of size, have biases in attenuation, absorption, and scattering, reaching values as high as 270%, generally being within about 50% to that of population of equal volume spheres. While not as large as for monodispersions, these biases are significant and very often overestimate, implying that populations of spherical particles perform poorly as an average, unbiased model.

IMPACT/APPLICATIONS

The ability to understand the impact of shape on marine optical properties will improve our interpretation of optical measurements in general and ocean color remote sensing in particular.

TRANSITIONS

The forward phase functions will be available to scientists employing LISST for particle sizing.

PUBLICATIONS

Agrawal, Y.C., Amanda Whitmire, Ole Mikkelsen, and H.C. Pottsmith, 2007: Light Scattering by Random Shaped Particles and Consequences on Measuring Suspended Sediments by Laser Diffraction; JGR (*in revision*)

Agrawal, Y.C., A. Whitmire, and H. C. Pottsmith, 2006: Light Scattering By Random, Irregular Shaped Terrigenous Sediment Particles, Ocean Optics XVIII, Montreal, Canada.

Clavano, W. R., E. Boss and Y. Agrawall, 2006 (Ocean Sciences meeting). Anisotropy in the backscattering of marine-like particles: indications of size and shape. http://dspace.library.cornell.edu/bitstream/1813/2656/1/2006OS36I-06_letter.pdf.

Clavano, W.R., E. Boss, and L. Karp-Boss, 2007. Inherent Optical Properties of Non-Spherical Marine-Like Particles - From Theory to Observations. Oceanography and Marine Biology: An Annual Review, 2007, 45, 1-38.

Karp-Boss, L., L. Azevedo, and E. Boss, 2007. LISST-100 measurements of phytoplankton size distribution: evaluation of the effects of cell shape. In press, Limnology and Oceanography, methods.

Konert, M., and J. Vandenberghe (1997), Comparison of Laser Grain Size Analysis with Pipette and Sieve Analysis: A Solution for the Underestimation of the Clay Fraction, *Sedimentology*, *44*, 523-535

Thorne, Peter D., Y. C. Agrawal and D. Cacchione, 2007: A comparison of acoustic backscatter and laser diffraction measurements of suspended sediments, IEEE J. Ocean. Engg., **32,**n 1, pp.225-235.

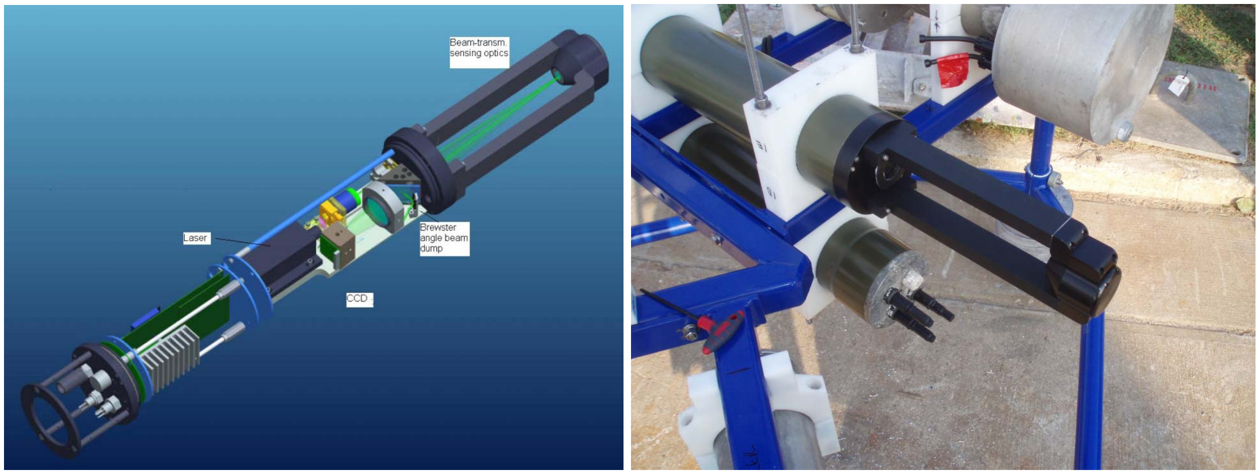

Figure 1: Optics details of the LISST-Back (left) and mounted on a tripod before deployment at MVCO (right). As seen on left, the optical path is set to 20 cm and a beam attenuation sensor is employed. This eliminates need for vignetting correction. The hardware photo shows a separate battery case below the instrument case as well.

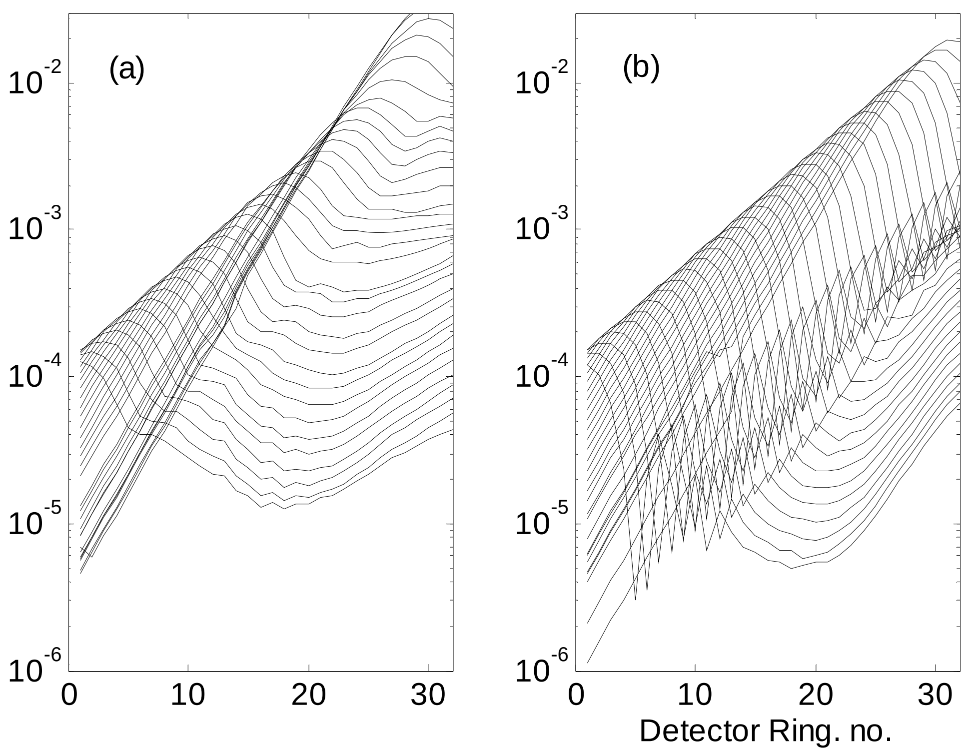

Figure 2: The scattering of light per unit volume concentration, by random shaped particles (left) and spheres (right) as seen by the logarithmic ring detectors of the LISST-100 instrument. In all, 32 log-spaced size classes were studied over a 200:1 size range, so 32 curves are shown. Note that secondary maxima seen with spheres vanish with random shaped particles.

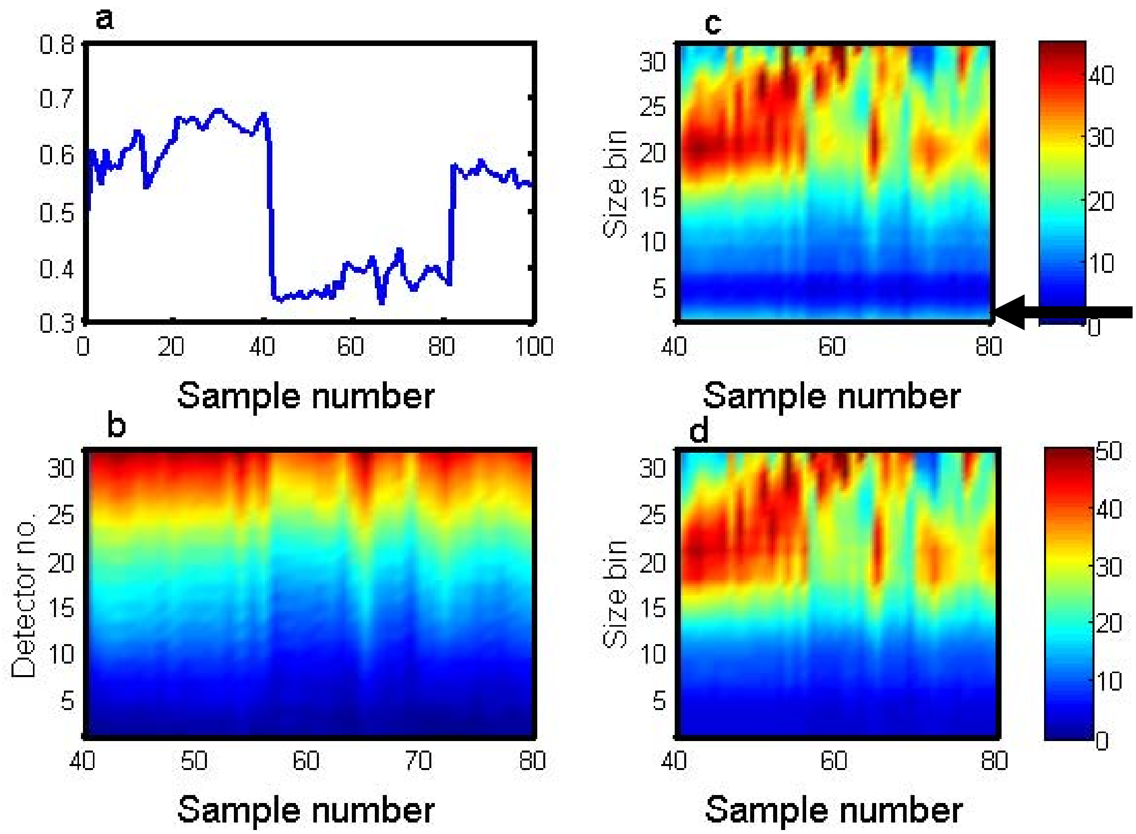

Figure 3: This figure displays the effect of using proper forward model for inverting multi-angle scattering to construct size distribution. The optical transmission measured by a LISST-type instrument (a) shows a dip in optical transmission corresponding to an intense part of a storm event. The multi-angle scattering during the event is shown in (b). When this is inverted with an equivalent spheres model (c) a rising edge appears at the small size bins (arrow). When the inversion employs the proper random shape matrix for inversion, the rising edge artifact disappears (d).

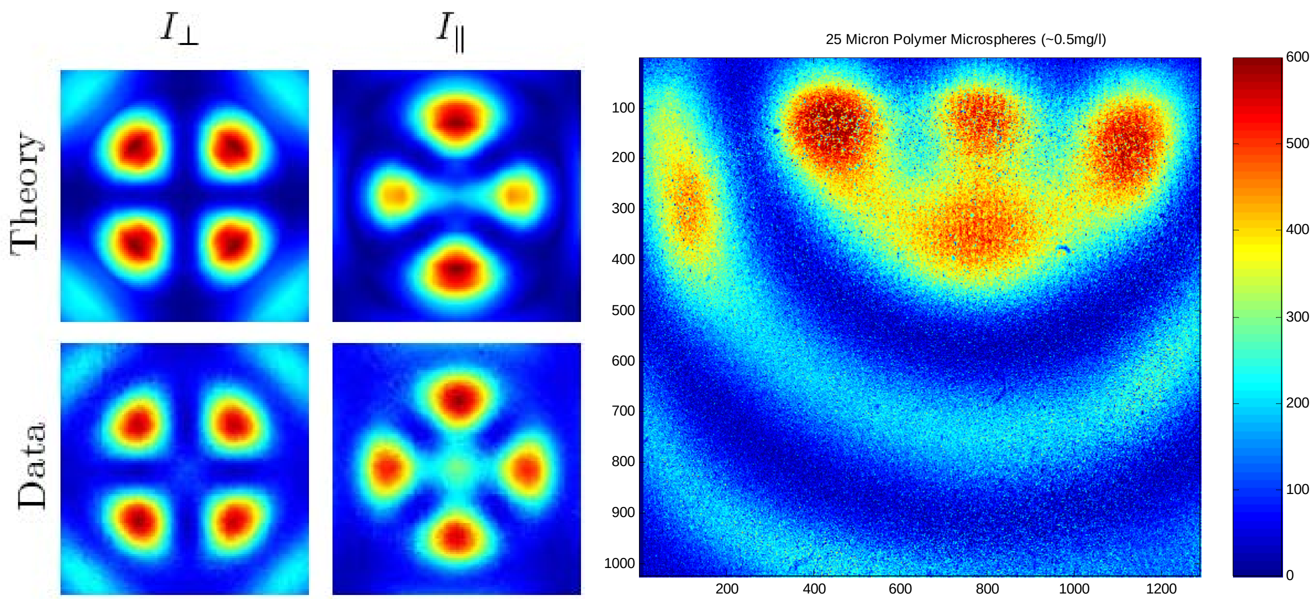

Figure 4: Backscattering by spherical particles and azimuthal dependence of scattering. On right, intensity on the focal plane of a receiving backscatter lens is displayed. Oscillations can be seen in scattering angle near 180^o and in azimuth. On left, with the image of the focal plane centered on the imaging array, a strong resemblance is found between measurement and data. Polarization dependence is striking (and consistent with theory, Clavano et al. 2007).

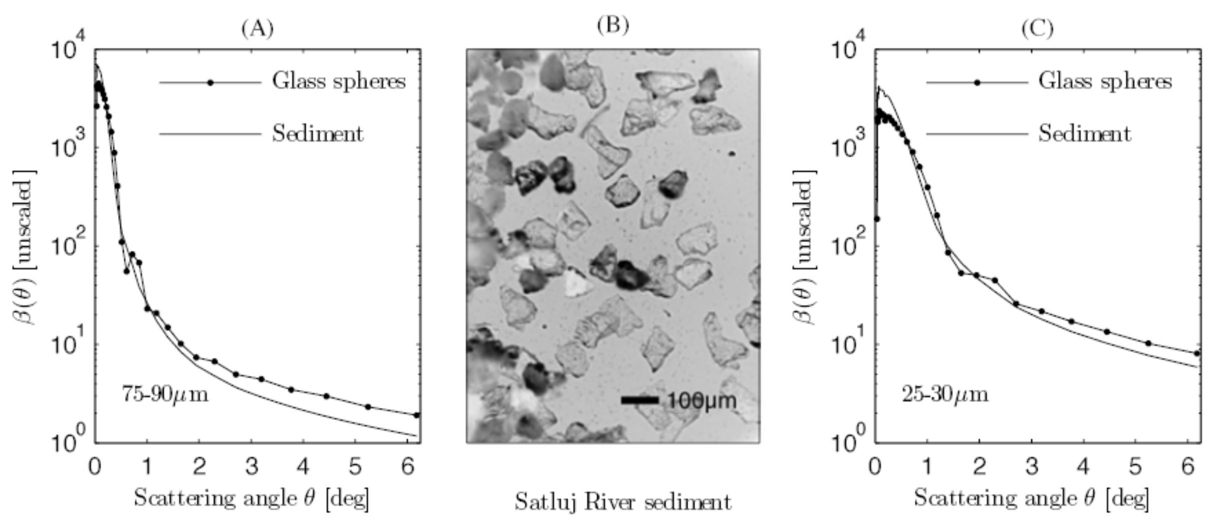

Figure 5. Measurements of near-forward scattering. (A) is a comparison of the shape of the near-forward scattering between sorted particles (Satluj River sediment; solid line) and glass spheres (line with dots) 75-90µm in size. An image of the particles used in the measurement of the sediment in (A) is presented in (B). (C) is a comparison between sediment (solid line) and glass spheres (line with dots) 25-30µm in size. Note the narrowing of the scattering pattern and absence of secondary maximum for the non-spherical natural particles (solid lines) compared to polydispersions of spheres sieved similarly (lines with dots). Scattering measurements were performed with the LISST-100 instrument.